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Measuring Hydraulic Conductivity Using Geotechnical Centrifuge

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Abstract: This study investigated the validity of hydraulic conductivity value using Mini Column Infiltration Test. Granitic residual soils from Broga Selangor, Malaysia were tested to obtain the hydraulic conductivity value in relatively shorter time. Soil samples were physically characterized before being tested using Centrifuge Mini Column Infiltration Technique. A normal 1-g Falling Head Permeability Test (K_f) was also being performed as a comparison with hydraulic conductivity value from Centrifuge Test (K_{cen}). For centrifuge test (K_{cen}), there were three factors involved; rotation speed, soil thickness and type of solution (single or mixture solution). Hydraulic conductivity value from Centrifuge Test (K_{cen}) also was highly depending on the Scale Factor Value (SFV). The results from Centrifuge Test showed that the higher rotation speed, the lower SFV would be. Hydraulic conductivity was decreasing with an increasing of rotation speed. The increment of soil thickness also contributed to the decrement of SFV and hydraulic conductivity value. Thus, the hydraulic conductivity value would be more accurate when higher rotation speed and higher soil thickness were applied. Hydraulic conductivity, K_{cen} for a single solution also showed higher values compared to mixture solutions. However, some of hydraulic conductivity value (K_{cen}) showed overestimated values due to the presence of cracks in the soil (mudcakes). Most of the scale factors gave low values ($x<1.00$) which meant x values were close to unity. The value of hydraulic conductivity for 1-g Permeability Test (K_f) was 2.08×10-6 m/s. While for 10mm soil thickness and 2500 RPM (1440 -g) velocity of a single solution, the value of hydraulic conductivity (K_{cen}) was 6.82×10^{-4} m/s. Since the scale factor obtained was less than 1 (x = 0.74), the value of K_{cen} could be used as a valid number to replace the value of K_f from 1-g Permeability Test. This study concluded that by using scale factor, the relationship between HCV from Centrifuge Tests and Falling Head Permeability Tests could be known; thus, Centrifuge modeling could be developed as a valid method in determining the hydraulic conductivity of the soils.

Keywords: Hydraulic Conductivity, Mini Column Infiltration Test, Granitic Residual Soil

Introduction

Centrifuge modeling has been used over the decades in many aspects to characterize the soil behaviors (Culligan, 1996). This method was chosen because of its ability to model complex natural systems in a controlled laboratory environment (Wan Zuhairi and Muchlis, 2012). By using a centrifugation, Darcy's velocity in a Centrifuge model was tested at N times, Earth's gravitational acceleration (g) was N times the unit discharged in the prototype provided that the soil in the model and the prototype soil had the same intrinsic permeability (Arulanandan *et al*., 1988; Emidio *et al*., 2002). According to Di Emidio *et al*. (2012; Singh and Gupta, 2002), Centrifuge Test could also be used to estimate the hydraulic conductivity of geotechnical materials in accelerated gravity conditions, reproduce the prototype vertical effective stresses in the soil samples and reduce the testing time. The purpose of this research was to validate hydraulic conductivity value obtained from mini column infiltration using mathematical model.

Materials and Methods

This study utilized geologic material which was granitic residual soil (BGR) taken from Broga, Selangor. This soil was air-dried and later sieved to 0.125 mm before it could be used for other analysis.

Falling Head Permeability Test

The falling head Permeability Test was conducted according to ASTM D-2434 (1984) method.

Mini Column Infiltration Test

Mini column infiltration by using a small geotechnical Centrifuge was conducted based on Antoniadis *et al*. (2007) method. A standard solution with 500±25 mg L^{-1} concentration of Cadmium Nitrate; $Cd(NO_3)_2$, was prepared. Soil sample weighed 20g has been added with de-ionized water to make it slurry. It was left overnight before transferred to the column cell. Sample was centrifuged and sedimented soil layer called 'mudcake' appeared. 5 mL^{-1} (equivalent to 1 pore volume) of influent solution of $Cd(NO_3)_2$ was added to upper part of the column. The cell was centrifuged until all parts of solution passed through the 'mudcake' layer. This procedure has been continued until 60 pores water volume was reached. For this test, different G-forces (230-g, 520-g, 920-g and 1440-g) and soil thicknesses (10g, 15g and 20g) were applied. The effluent solutions were collected and measured using Couple Plasma Mass Spectroscopy (Perkin Elmer Model OPTIMA 3000 with auto sampler).

Relationship for Hydraulic Conductivity in Centrifuge and 1-g Permeability Test

The relationships between hydraulic conductivity for both Centrifuge Test (K_{cen}) and 1-g Permeability Test (K_f) were shown in equation 1 and 2:

$$\frac{K_{cen}}{K_f} = N^x \quad (1)$$

where, K_{cen} and K_f are the values of hydraulic conductivity obtained from Centrifuge Test and Falling Head Permeability Test respectively. N is an achieved acceleration level, x is the scale factor for hydraulic conductivity respects to 1-g:

$$x = \frac{In \frac{K_{cen}}{K_f}}{In\, N} \quad (2)$$

Equation 2 are derived from equation 1 in order to calculate the scale factor; x. Based on Singh and Gupta (2002), by obtaining the scale factor, the correlation between K_{cen} and K_f could be identified.

Results and Discussion

Physical properties of the soil have been tested according to British Standard Method, BS1377 (1990) to investigate the physical characteristics of it. All the physical tests were tabulated in Table 1 and were run a prior Mini Column Infiltration Test. Granitic residual soil (BGR) had higher percentages of sand ranged between 54%-63% and according to Unified Soil Classification System (USCS), it was classified as sandy silt material. According to Zarime *et al* (2014), coarse-grained soils exhibited a lower heavy metal absorption tendency compared to fine-grained soil. The granitic residual soil was chosen to be tested due to its low permeability. The Atterberg limit (plasticity index), specific gravity, maximum dry density and 1-g Permeability Test also showed moderate values ranged between 9.90%-11.99%, 2.50-2.59, 1.75 g/cm^3 and 2.08×10^{-06} respectively. High plasticity indicates higher absorption capability (Zulfahmi *et al*., 2011). Moderate value of specific gravity (2.50-2.59) shows granitic residual soil to have a moderate particle size (Chalermyanont *et al*., 2009).

Table 2 shows the hydraulic conductivity values and scaling factors in a Mini Geotechnical Centrifuge. The results showed that the hydraulic conductivity (K_{cen}) was highly depended on the SFV. For 10mm soil thickness in 500ppm mixture solution, increased rotation speed from 1000 RPM to 2500 RPM, showed the decreased of scale factors; x = 1.07 (1000 RPM), x = 0.94 (1500 RPM), x = 0.71 (2000 RPM) and; x = 0.63 (2500 RPM). Hydraulic conductivity of the soil also decreased with the increasing of rotation speed. The reason of this behaviour was due to the decreased of the soil's void ratio (Di Emidio *et al*., 2012). According to Poulos (1988), the increased of the rotation speed in the centrifuge would increase the driving force applied on the samples, thus the void ratio would decrease. Therefore, when the rotation speed increased, hydraulic conductivity of the samples would be decreased.

Table 1. Physical properties of granitic residual soil

Physical characteristics	BGR
Particle size distribution	
Sand (%)	54-63
Silt (%)	32-42
Clay (%)	1-6
Atterberg limit	
Plastic limit (%)	38.01-38.61
Liquid limit (%)	48.50-50.00
Plasticity index (%)	9.90-11.99
Specific gravity	2.50-2.59
Max dry density (g/cm^3)	1.75
Soil classification (USCS)	Sandy silt
Permeability (m/s)	2.08×10^{-06}

Table 2. Hydraulic conductivity values (cm/s) and scale factors

Soil Weight (g)	Soil thickness (mm)	Rotation Speed (RPM)	G-Force (-g)	Single solution (500 ppm) K_{cen} (m/s)	*N*	*x*	Mix solution (500 ppm) K_{cen} (m/s)	*N*	*x*	Mix solution (100 ppm) K_{cen} (m/s)	*N*	*x*	Falling head permeability *(Kf*
10	10	1000	230	2.23×10^{-3}	1000	1.01	3.38×10^{-3}	1000	1.07	2.17×10^{-3}	1000	1.01	
		1500	520	4.51×10^{-2}	1500	1.37	2.07×10^{-3}	1500	0.94	6.89×10^{-4}	1500	0.79	
		2000	920	8.62×10^{-4}	2000	0.79	4.56×10^{-4}	2000	0.71	3.57×10^{-4}	2000	0.68	
		2500	1440	6.82×10^{-4}	2500	0.74	2.89×10^{-4}	2500	0.63	1.31×10^{-4}	2500	0.53	
15	15	1000	230	2.90×10^{-3}	1000	1.05	-	-	-	9.96×10^{-4}	1000	0.89	2.08×10^{-6} m/s
		1500	520	1.25×10^{-3}	1500	0.87	-	-	-	3.50×10^{-4}	1500	0.7	
		2000	920	8.82×10^{-4}	2000	0.8	-	-	-	2.09×10^{-4}	2000	0.61	
		2500	14402	3.80×10^{-4}	2500	0.65	-	-	-	7.50×10^{-5}	2500	0.46	
20	20	1000	230	1.67×10^{-2}	1000	1.3	-	-	-	6.64×10^{-3}	1000	1.17	
		1500	520	2.09×10^{-4}	1500	0.63	-	-	-	4.37×10^{-5}	1500	0.42	
		2000	920	6.11×10^{-4}	2000	0.75	-	-	-	5.40×10^{-5}	2000	0.43	
		2500	1440	1.01×10^{-3}	2500	0.79	-	-	-	2.76×10^{-6}	2500	0.04	

Notes: N= acceleration level and x= scale factor for hydraulic conductivity

For 1500 RPM rotation speed of a 500 ppm single solution, an increment of soil thickness showed the decrement of scale factors and hydraulic conductivity values; (10mm: $x = 1.37$, $K_{cen}= 4.51\times10^{-2}$ m/s, 15mm: $x = 0.87$, $K_{cen}= 1.25\times10^{-3}$ m/s and 20mm: $x = 0.63$, $K_{cen}= 2.09\times10^{-4}$ m/s). Increasing of soil thickness has decreased the high energy sites where low energy sites were filled with larger ions fractions and caused the decreasing of metal adsorption from pollutants, q_e and hydraulic conductivity values, $K_{cen.}$ Hydraulic conductivity, K_{cen} for a single solution also showed a higher value compared to mixture solutions. For example, for 1500 RPM rotation speed and 10mm soil thickness, hydraulic conductivity value for single solution was $K_{cen}= 4.51\times10^{-2}$ m/s while for mixture solution was $K_{cen}= 2.07\times10^{-3}$ m/s. This was due to the competition for heavy metal ions adsorption in mixture solutions. Thus, it reduced the adsorption of heavy metal and subsequently lowered the K_{cen} values. For single solution, there is no competition for adsorption of metals, thus the value of K_{cen} increases (Wan Zuhairi and Abdul Rahim, 2007).

Most of the scale factors were showed to be low values (x<1.00) which meant x values were close to unity. For the scale factor (x >1.00), the hydraulic conductivity (K_{cen}) the values were overestimated due to the presence of cracks in the soil (mudcakes) during centrifugation. For 10mm soil thickness and 2500 RPM (1440 -g) speed rotation of a single solution, the values of hydraulic conductivity (K_{cen}) and scale factor were 6.82×10^{-4} m/s and 0.74 respectively. While hydraulic conductivity for 1-g Permeability Test (K_f) provided value of 2.08×10^{-6} m/s. This indicated that 1-g permeability (K_f) to has good correlations with permeability from Centrifuge Test (K_{cen}) since the scale factor obtained was less than 1 (x = 0.74). This study proved the Hydraulic Conductivity Values from the Centrifuge Tests can be developed as a valid method in determining the hydraulic conductivity of the soil in a short period.

Conclusion

This study highlighted the capability of Centrifuge modeling in measuring the hydraulic conductivity (K_{cen}) in a short period of time. Results have shown that hydraulic conductivity (K_{cen}) was highly depending on the SFV. Hydraulic conductivity was decreasing with an increasing of rotation speed, while increment of soil thickness decreased the SFV and hydraulic conductivity value. Hydraulic conductivity, K_{cen} for a single solution also showed higher value compared to mixture solutions. The low values of scale factor (x<1.00) showed that x values were close to unity, while for scale factor (x >1.00), it showed the overestimated hydraulic conductivity values (K_{cen}). This was due to the presence of cracks in the soil (mudcakes) during the centrifugation. The study also concluded 1-g permeability (K_f) to has good correlations with permeability obtained from Centrifuge Test (K_{cen}). Thus, Centrifuge modeling can be developed as a valid method to determine the hydraulic conductivity of the soil.

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Author’s Contributions

Nur Aishah Zarime: Conducting the experimental work and drafting this paper.

Wan Zuhairi Wan Yaacob: Is the main supervisor of the study and revise the article.

Ethics

This article is an original and contains unpublished materials. All authors have read and approved this manuscript and no ethical issues involved.

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